

Design of Low-Flow Channels



by Craig Fischenich¹

August 2002

Complexity

Low		Moderate		High

Value as a Planning Tool

Low		Moderate		High

Cost

Low		Moderate		High

OVERVIEW

Maintenance or restoration of physical aquatic habitat in streams during critical periods can often be accommodated with the development of low-flow channels, designed to concentrate flows and increase channel velocity and depth during low-flow periods. A procedure for the first-order approximation of a stable low-flow channel form based upon physical reasoning, empirical evidence, and constraints common to low-flow channel projects is presented in this technical note. Topics discussed include simplifying assumptions, limitations, and applicability.

PLANNING

Unaltered natural streams support healthy aquatic ecosystems due largely to their habitat complexity. Alternate pools and riffles, irregular planforms, eroding banks, overhanging vegetation, boulders, logs, and variable substrate all contribute to diversity of habitat within and along the channel. Natural channels are scaled to provide this diversity for a wide range of flow conditions.

In contrast, channels modified for flood control often have relatively uniform depths and velocities and usually contain few instream and streambank features that provide habitat. The same situation arises for urban streams that have enlarged due to increased runoff; they are "overfit" during baseflow conditions and display small, featureless channels. This lack of diversity in modified and enlarged channels negatively influences the aquatic ecosystem.

Attaining habitat diversity in such channels requires the incorporation of instream and streambank features and cover devices that create depth, velocity, and cover diversity. These features are most effective when they contribute to natural and diverse channel conditions during low flow but have little impact upon the ability of the channel to convey flood flows and sediment. Furthermore, these features must possess the necessary stability to withstand the high velocities typically associated with modified channels. A successful design concept that improves habitat conditions but has negligible effects upon flooding is the combination of streambank and instream features to form a diverse, stable, low-flow channel (Figure 1).



Figure 1. Low-flow channels can maintain natural stream characteristics within an enlarged floodway

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Restoration of physical aquatic habitat in streams during critical periods can often be accomplished with low-flow channels designed to concentrate flows, increase channel velocity and depth, and generally maintain the characteristics of a natural channel within an enlarged flood control channel. Structural measures such as bank protection, flow deflectors, and sills are generally required to stabilize the channel and provide habitat diversity. In addition to the usual design requirements for these structures, a structural layout is needed that allows the stream to adopt a form consistent with the project objectives. Designers must translate physical habitat objectives into hydraulic and geomorphic criteria, which, in turn are used to select structural measures (Fischenich et al. 1994). Unfortunately, no procedure has been proposed to accomplish this.

In this technical note, a stable channel is defined as a channel that, over an engineering time scale, retains its planform, cross-sectional geometry, and grade with allowance for temporal variability about a mean that displays no trends. Existing techniques for predicting the hydraulic geometry of stable alluvial channels can be placed into two categories: 1) empirical regime equations derived from regression analyses of observed channel geometry, and 2) analytical models that attempt to model rivers on a rational basis using theoretical considerations. Knighton (1984), Chang (1988), and Mueller and Dardeau (1990), among others, present summaries of many of these techniques. The early regime equations generally relate some two-variable combination of velocity, width, depth, slope, area, hydraulic radius, perimeter, or discharge as a power function and can be generalized in the form of Equations 1 through 3, where by continuity, $ack=1$ and $b+e+m=1$.²

$$W = aQ^b \quad (1)$$

$$D = cQ^e \quad (2)$$

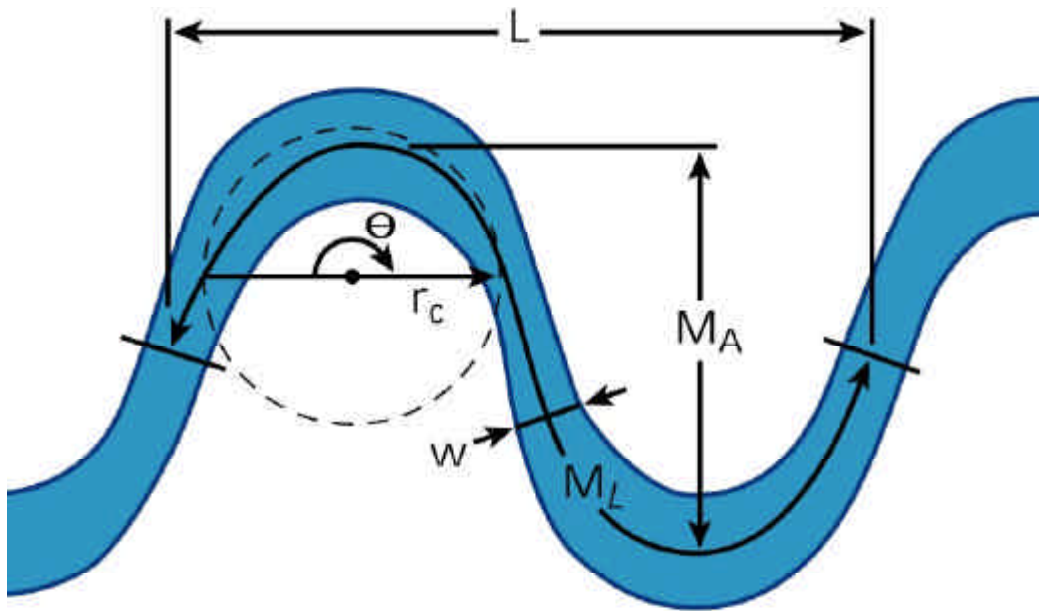
$$V = kQ^m \quad (3)$$

Analytical procedures include the method of maximum permissible velocity, the critical shear stress method, and the so-called "rational" regime equations that use tractive force theory, resistance and sediment transport laws, minimum stream power, maximum sediment transport capacity, similitude, bank stability analyses, and other concepts to overcome the fact that alluvial channels have more degrees of freedom than available relations for solution. Wargadalam (1993) showed that the existing body of literature on the subject could be reduced to no fewer than 176 equations describing depth, width, velocity, and slope in the form:

$$W, D, V, \text{ or } S_0 = a_1 Q^{b_1} d_s^{c_1} Q_s^{e_1} \quad (4)$$

Despite the considerable effort expended in formulating these many approaches to stable channel geometry prediction, none are suitable for the development of stable low-flow channel designs. The reasons for this include: 1) no consideration of habitat requirements, 2) empiricism, 3) applicability only to straight channels, and 4) theoretical flaws. Perhaps the greatest limitation of many of these techniques is that they consider width, depth, and slope to be the only degrees of freedom and do not account for the full dynamic nature and multi-dimensionality of fluvial systems. A minimal description of channel morphology requires that its grade, planform, cross-sectional geometry, and some measure of channel resistance be parametrically defined. Channel grade can be described by the bed slope S_0 and resistance can be described by the friction slope S_f . Channel planform requires at least two parameters, e.g., sinuosity and meander arc length. To uniquely define the cross-sectional geometry of a channel requires that at least one variable in addition to the width and depth be specified. Examples of a third variable are maximum depth, bank slope, and a channel shape factor. Figures 2 and 3 show the parameters used in describing channel geometry and planform in this paper.

² See page 9 for mathematical notation.



L meander wavelength
 M_L meander arc length
 w average width at bankfull discharge
 M_A meander amplitude
 r_c radius of curvature
 Θ arc angle

Figure 2. Channel planform definition

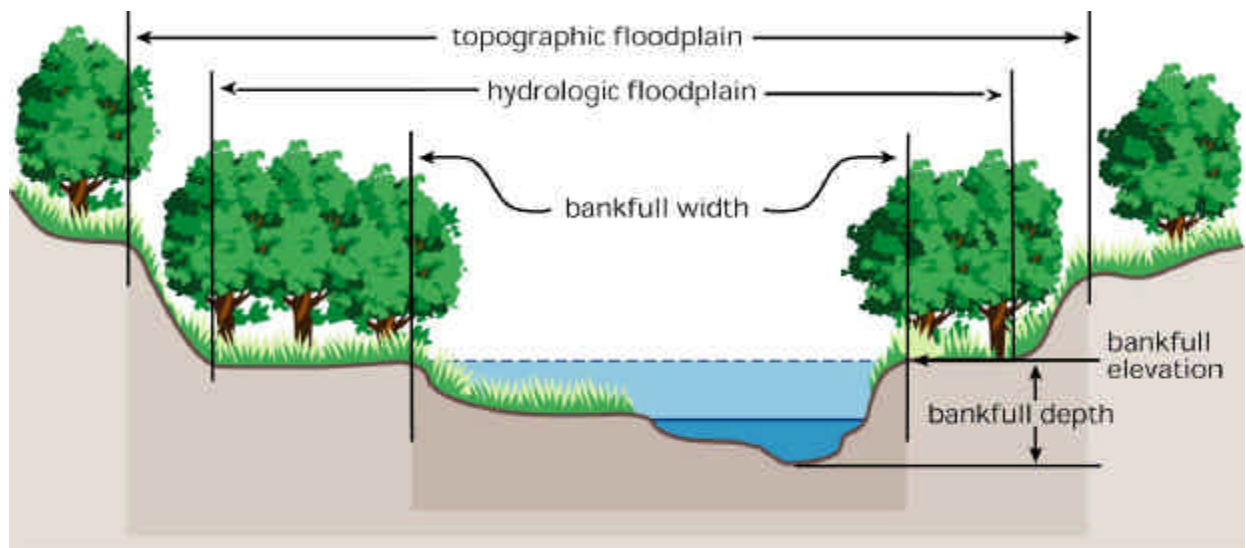


Figure 3. Channel cross section definition

PROCEDURE FORMULATION

Fundamental Considerations

Both Cartesian and curvilinear coordinate systems are used in the formulation of the procedure. The principal axis x in the Cartesian system defines the centerline of the meandering pattern in the downstream direction for planform analysis; it is aligned with the stream and is horizontal for cross section and grade analyses. The y and z axes alignments are with the vertical and horizontal, both normal to the flow. In the curvilinear system, the sinuous axis s follows the centerline of the stream, and the transversal direction remains orthogonal to the principal axis in the horizontal.

Analytical determination of the hydraulic geometry for alluvial channels can be accomplished only if applicable physical and empirical relations are sufficient to describe the unknowns or degrees of freedom. Two characteristics of low-flow channels help to satisfy this requirement. First, habitat analyses, based on biological criteria, are used to establish a minimum flow depth and an optimum velocity for the channel. Second, instream and streambank structures are typically used to stabilize the channel, provide cover and substrate, and generate diversity in velocity. Given these constraints, physical reasoning, geometric analyses, and a few semiempirical relations, a solution is possible.

A fundamental assumption in the application of this procedure is that sand bed channels tend toward a meandering planform that can be described by a sine-generated curve. Langbein and Leopold (1966) used the theory of minimum variance to show that the most probable path of a meandering stream was a sine curve. Julien (1985) showed that the fundamental shape of meandering planforms could be evaluated based on the separation of the boundary layer near the inner bank and the rate of energy dissipation. Julien (1985) demonstrated that among all possible geometries, with the exception of a straight channel, boundary

separation and the rate of energy dissipation are minimized by a simple sine-generated function. Approaches based upon the Kinoshita equation, Von Schelling's curve, and Fargue's spiral can also be reduced to a form of sine-generated curve. The sine-generated function has thus been shown to fit the shape of meanders on stable rivers quite well and is the most convenient expression to use. The corresponding meandering pattern, with reference to Figure 2, can be written as:

$$\frac{dq}{dx} = -a_1 \sin \frac{2ps}{M} \quad (5)$$

A second fundamental assumption is that the flow is approximately uniform in the streamwise direction. This assumption allows the bed, water, and friction slopes to be equated and permits the use of a uniform rating equation. The final assumption relates to sediment continuity, which must be preserved to meet the stable channel definition. The proper approach to ensure that continuity is met is to perform both longitudinal and transversal sediment transport analyses. A simplified approach is used, wherein continuity is approximated by setting the bed shear stress at the critical value for the mean bed sediment size.

Procedure

Because low-flow channels are developed for environmental purposes, the first step is to conduct hydrologic analyses to establish the target or design discharge. Instream Flow Incremental Methodology (IFIM) analyses, habitat suitability curves, or other biological criteria are then used to establish target values of velocity and depth. Realizing optimum values for both the depth and velocity objectives is unlikely; therefore, one must be established as a critical parameter. The most common case, in which a critical minimum depth is established and an optimum velocity target identified, is used here. Simple modifications to this procedure will accommodate other cases, such as a maximum velocity and an optimum depth.

Grade: The criterion of beginning of motion establishes a threshold corresponding to a condition of maximum allowable shear. The ratio of forces on an individual sediment grain on a sloping bed is evaluated to define the dimensionless shear stress called the Shields number:

$$t_* = \frac{gR_h S_f}{(g_s - g)d_s} \quad (6)$$

The critical value of the Shields number τ_{*c} corresponding to the beginning of motion, was determined by Shields (1936). For particle Reynolds numbers greater than 200, $\tau_{*c} \cong 0.05$. The widely accepted Shields diagram is used as a basis for many stable channel design techniques despite complexities encountered in its application to irregular channel geometries. Given the depth constraint and sediment size measurements, the maximum allowable friction slope for longitudinal stability can be computed from Equation 6 by setting the hydraulic radius R_h equal to the minimum depth and setting $\tau_{*c} = 0.05$. For sands and gravels of specific gravity $G = 2.65$, this relation reduces to:

$$S_f = 0.0825 \frac{d_{50}}{D} \quad (7)$$

For uniform flow, channel grade can be equated to the friction slope, and either can be related to the sinuosity of the low-flow channel and measurement of the bed slope of the parent channel S_c :

$$S_o = S_f = \frac{S_c I}{M} \quad (8)$$

While this must be the reach-wise average bed slope of the low-flow channel, variation about this average to accommodate pool-riffle sequences is possible if the resultant reaches have the requisite transport capacities to ensure no aggradation or deposition. This first approximation of the channel grade ignores transversal stability,

which can be incorporated into the analysis as discussed later.

Planform: With the allowable friction slope computed by Equation 7 and a measured thalweg slope of the parent channel, Equation 8 is used to establish the ratio of the meander wavelength to the arc length. Again, assuming a sine-generated curve for the planform shape and a constant velocity along the meander length, Equation 5 can be integrated for θ :

$$q = \frac{Ma_2}{2pV} \cos \frac{2ps}{M} + c_2 \quad (9)$$

in which the maximum angle of the streamline with the downstream valley θ_m corresponds to:

$$q_m = \frac{Ma_2}{2pV} \quad (10)$$

The meander wavelength is computed from the following relation:

$$I = \int_0^M \cos q ds \quad (11)$$

Defining a nondimensional curvilinear distance, $s' = s/M$, and rearranging with Equations 9 and 10 gives:

$$\frac{I}{M} = \int_0^1 \cos[q_m \cos(2ps')] ds' \quad (12)$$

The sinuosity is defined as the ratio M/λ and increases gradually with θ_m . Equation 12 has been integrated numerically and the results are shown in Figure 4. Figure 4 (or Equation 12) can be used to determine the maximum angle of the streamline θ_m . For a given friction slope and the assumption of a sine-generated curve, the shape, sinuosity, and maximum angle of the streamline are defined. The scale must still be determined even though the shape of the planform is known.

The radius of curvature varies along the bend as a cosecant function, and the minimum radius of curvature r_m is reached when the cosecant function equals unity. The ratio of the wavelength to the minimum radius of curvature λ/r_{cm} is

$$\frac{l}{r_m} = \frac{2pq_m l}{M} \quad (13)$$

The meander amplitude A_m as defined in Figure 2 is evaluated analytically by the following integral:

$$A_m = 2 \int_0^{M/4} \sin q \, ds \quad (14)$$

The ratio of wavelength λ to the meander amplitude A_m is

$$\frac{l}{A_m} = \frac{\int_0^1 \cos[q_m \cos(2ps')] \, ds'}{\frac{1}{4} \int_0^1 \sin[q_m \cos(2ps')] \, ds'} \quad (15)$$

Equations 13 and 15 have been integrated numerically and are also shown in Figure 4. The ratio λ/A_m is a function of θ_m that increases rapidly when θ_m exceeds 90° and reaches a value of 3.25 at the meander cutoff ($\theta_m \cong 125^\circ$). The relations expressed in Equations 13 and 15 further define the planform shape, but an additional relation is needed for the size. One relation can be formulated on the basis of a limiting radius of curvature to ensure cross-sectional stability. This procedure is tedious and requires an analysis of the transversal shear stress distribution and sediment transport along the meander path. In the case of low-flow channel design, a simpler relation is available in that the meander amplitude is constrained by the width of the parent channel. The latter approach has been adopted.

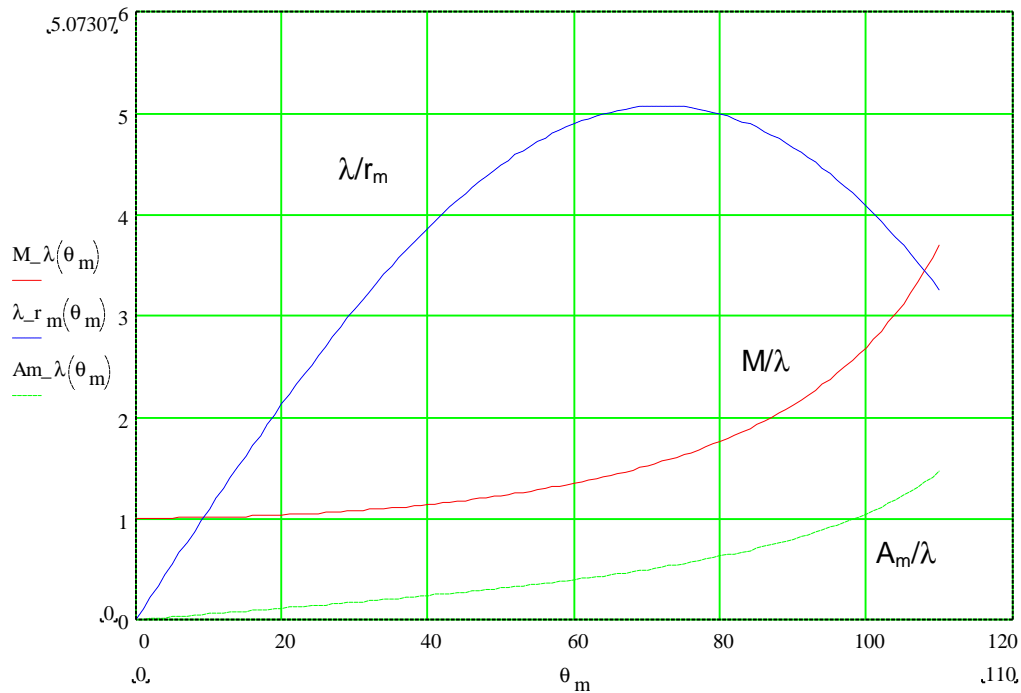


Figure 4. Planform relations

Low-flow channels are typically constructed by placing longitudinal bank protection, flow deflectors, and sills within a parent channel. The width of the parent channel at the low-flow channel elevation defines a maximum meander amplitude with no erosion of the parent banks. This is only an upper limit, and any $0 < A_m \leq W_c$ will meet the shape requirements. From a practical standpoint, however, constructability and habitat benefits are optimized with the larger amplitudes. The amplitude should be set at some fraction (perhaps 90 percent) of the parent channel width, minus the encroachment of longitudinal revetment structures. With this value of A_m , either Figure 4 or Equations 12 and 15 can be used to determine the meander arc length and wavelength. The channel planform can then be laid out, and structures can be selected and located in the normal fashion.

Cross Section: Although habitat criteria were used to establish a target velocity, a rating equation is used to determine the mean velocity for the defined channel. The Manning-Strickler Equation can be used to find mean velocity V :

$$V = \frac{21.1}{d_{50}^{1/6}} D^{2/3} S_f^{1/2} \quad (16)$$

This mean velocity must be evaluated on the basis of habitat considerations. If it is unacceptable, the depth must be adjusted, and the entire procedure must be iterated until an acceptable value of velocity is obtained. When the velocity is within acceptable limits, the principle of continuity is applied to determine the cross-sectional area:

$$A = \frac{Q}{V} \quad (17)$$

An infinite number of cross-sectional shapes can be developed within the area and depth constraints given. However, naturally stable sand bed channels tend to have certain

shapes with respect to their position, commonly trapezoidal in the crossings and a skewed parabola in the bendways. Investigators have described these shapes in terms of transversal sediment transport, force analyses, and critical transversal shear stress distribution. From a practical standpoint these complex cross sections would be difficult to construct, and the width varies little from that of a trapezoidal section. As a first approximation, a trapezoidal section with three-to-one side slopes should be used to establish the channel bottom width:

$$W = \frac{A}{D} - 3D \quad (18)$$

DESIGN REFINEMENT AND IMPLEMENTATION

The success of this technique on sand-bed channels is virtually nonexistent due to the high transport rates of sediment under nearly all flow regimes. Success in gravel-bed streams is only slightly higher than for sand-bed streams (Fischenich 1993). Therefore, accomplishment of project objectives can be significantly improved by using structural measures such as bank protection, flow deflectors, and sills to stabilize the planform, cross-sectional geometry, and bed profile of the channel. In addition to the usual design requirements for these structures, the designer must select an appropriate structural layout with the objective of causing the stream to adopt a form that is consistent with the project objectives. Projects are too often formulated with little or no thought given to the placement of structures; as a consequence, both structural and channel stability are compromised. With no assurance of the future form of the channel, projected benefits cannot be assured.

APPLICABILITY AND LIMITATIONS

A procedure for the first-order approximation of a stable low-flow channel form has been developed based upon physical reasoning, empirical evidence, and constraints common to low-flow channel projects. More sophisticated analyses would be warranted to design the channel as nearly like its stable form as possible. However, this procedure yields a reasonable estimate of the planform and grade of the channel and maximizes probability that natural transport processes will quickly re-form the cross section without impacts to the channel stability.

Many of the assumptions used in the formulation of this procedure are not always valid. For example, the Manning-Strickler Equation is assumed to apply, which further implies that the sediment is in the sand size range and that the flow is approximately uniform. Only the longitudinal shear stress is considered in this simplified analysis. A detailed analysis should also consider the transversal stress distribution, which usually results in a decrease in the allowable friction slope. Finally, section stability under a range of discharges has not been established. Such a determination would require that friction slope decrease with increasing depth and that transport capacity through the section match the inflowing load.

Despite these limitations, this method as presented yields a reasonable first-order approximation of the stable channel form. This "stable" channel configuration can be further evaluated using more sophisticated techniques. The proposed procedure yields a close approximation of natural occurrences and thus allows the stream to make minor adjustments that conform to its newly introduced geometry.

POINTS OF CONTACT

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NOTATION

A	cross-sectional area of the channel
A_m	meander amplitude
a, a_1, \dots	empirical coefficients
b, b_1, \dots	empirical coefficients
c, c_1, \dots	empirical coefficients
d_s	sediment size
D	average flow depth
D_c	average depth in parent channel
d_{50}	representative bed sediment size
e, k, m	empirical coefficients
Q	total discharge
Q_s	sediment load
r_m	minimum radius of curvature
R_h	hydraulic radius
M	wavelength path distance
s	curvilinear longitudinal distance
s'	dimensionless curvilinear distance
S_f	friction slope
S_o	bed slope
S_c	bed slope of parent channel
V	cross-sectional average downstream velocity
W	channel width
W_c	parent channel width
w	curvilinear transversal coordinate
x	Cartesian longitudinal coordinate
y	vertical coordinate
z	Cartesian transversal coordinate
γ	unit weight of water
γ_s	unit weight of sediment
λ	meander wavelength
θ	angle of streamline with x
θ_m	maximum angle of streamline with x
τ_*	dimensionless Shields number
τ_{*c}	critical Shields number